Presentation

GLOBAL REFERENCE ATMOSPHERIC MODELS FOR AEROASSIST APPLICATIONS

Aleta L. Duvall[(1)], C. G. Justus[(1)], Vernon W. Keller[(2)]

[(1)]Morgan Research Corporation, NASA MSFC EV13/Morgan, Marshall Space Flight Center, AL, 35812 (USA)
Email: aleta.duvall@msfc.nasa.gov, jere.justus@msfc.nasa.gov
[(2)]Environments Branch, NASA MSFC EV13, Marshall Space Flight Center, AL, 35812 (USA)
Email: vernon.keller@nasa.gov

ABSTRACT

Aeroassist is a broad category of advanced transportation technology encompassing aerocapture, aerobraking, aeroentry, precision landing, hazard detection and avoidance, and aerogravity assist. The eight destinations in the Solar System with sufficient atmosphere to enable aeroassist technology are Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Saturn's moon Titan. Engineering-level atmospheric models for five of these targets - Earth, Mars, Titan, Neptune, and Venus - have been developed at NASA's Marshall Space Flight Center. These models are useful as tools in mission planning and systems analysis studies associated with aeroassist applications. The series of models is collectively named the Global Reference Atmospheric Model or GRAM series. An important capability of all the models in the GRAM series is their ability to simulate quasi-random perturbations for Monte Carlo analysis in developing guidance, navigation and control algorithms, for aerothermal design, and for other applications sensitive to atmospheric variability. Recent example applications are discussed.

1. INTRODUCTION

NASA's Vision for Space Exploration, unveiled in February, 2004, calls for a "building block" strategy of human and robotic missions to achieve new planetary and space exploration goals. According to NASA's strategic plan, space exploration beyond low Earth orbit will be implemented through a series of activities focusing on the Moon and Mars as key destinations. Robotic missions to the Moon will begin no later than 2008, followed by an extended human expedition as early as 2015. Lunar exploration will lay the groundwork for future human exploration of Mars and other destinations.

Among the activities deemed necessary to implement this vision are the development and demonstration of power generation, propulsion, life support, and other key capabilities required to support longer-duration missions. NASA Marshall Space Flight Center's (MSFC's) Advanced Space Transportation Program (ASTP) is charged with developing advanced propulsion technologies and concepts that have the potential to decrease trip times and reduce the weight of propulsion systems required for extended missions. One of the most promising technology categories is "propellantless" propulsion systems, or systems that rely on the natural resources of space and atmospheric environments for propulsion. Propellantless propulsion concepts include solar sails, plasma sails, momentum-exchange tethers, and electrodynamic tethers. Aeroassist technology also falls in this category.

Aeroassist technology encompasses a wide range of applications in which aerodynamic forces are used to improve or enable a mission concept that includes flight through a planetary atmosphere. Aeroassist applications include aerobraking and aerocapture for orbiters; direct aeroentry (both guided and controlled) for landers and probes; and aerogravity assist for space transport vehicles. These applications are in varying states of technology readiness. Aerobraking and direct aeroentry have been successfully demonstrated within the context of several NASA missions (e.g., Mars Reconnaissance Orbiter, Mars Odyssey, and Mars Exploration Rover). However, they require continued technology investment to enhance their proven capabilities.

Aerocapture and aerogravity assist have not been formally demonstrated. While aerogravity assist represents the most distant application, aerocapture technology elements have been in place and available for development since the 1960s. MSFC's ASTP is actively pursuing aerocapture as a technology investment area under the In-Space Propulsion (ISP) Program. The ISP has recently sponsored a series of detailed systems analysis studies for aerocapture design reference missions to Neptune [1], Saturn's moon Titan [2], and Venus. A systems analysis study for a Mars

Proc. '3rd International Workshop Planetary Probe', Anavyssos, Attiki, Greece, 27 June – 1 July 2005 (ESA SP-607, April 2006)

aerocapture design reference mission is currently in progress. Jupiter, Saturn, and Uranus are also candidates for future aerocapture design reference missions.

A common denominator in the development and enhancement of all aeroassist applications is the need for high-fidelity characterization of the target destination's atmosphere. Aerocapture, for example, uses aeromaneuvering during a single atmospheric pass to impart the delta-V (decrease in velocity) necessary to achieve a target apoapsis and inclination. A key aerocapture risk is atmospheric variability and uncertainty. Incorporation of atmospheric variability and uncertainty in trajectory simulations provides a mechanism for designing robust guidance, analyzing aerodynamics, and quantifying approach navigation errors. Engineering-level atmospheric models are NASA's accepted method for providing atmospheric characterization, particularly density characterization, in trajectory simulations.

For the ISP-sponsored studies, front-end development of engineering-level or "global reference" atmospheric models (GRAMs) for each of the target destinations was performed by MSFC's Environments Branch. Titan-GRAM and Neptune-GRAM were formalized in 2004; Venus-GRAM was formally released in March, 2005. These models join Earth GRAM (designated hereafter as GRAM) and Mars-GRAM in a series of atmospheric models collectively referred to as the GRAM series. A common characteristic of all these models is their ability to simulate seasonal and time-of-day variability and uncertainty through the application of quasi-random perturbations to mean atmospheric parameters.

MSFC's GRAM [3-8] and Mars-GRAM [9-11] have a robust legacy; the current versions are GRAM-99 and Mars-GRAM 2005 [12, 13]. Most recently, GRAM-95 and GRAM-99 have been utilized in atmospheric sensitivity analyses for the Genesis sample return mission. These analyses are of particular interest for current (e.g., Stardust sample return) and planned (e.g., Mars sample return) missions involving Earth atmosphere direct entry. Mars-GRAM 2005 was formally released in March, 2005 in support of aerobraking operations for the Mars Reconnaissance Orbiter (MRO).

The flexibility of the models in the GRAM series is best illustrated through examples of their diverse aeroassist applications. Most recently, Titan-GRAM was exercised within the context of a Titan aeroassist study sponsored by the NASA Engineering Safety Center (NESC). Titan-GRAM's role in the study, associated comparisons, and implications for future model development efforts are discussed below.

2. BASIS FOR TITAN-GRAM

Titan-GRAM is based primarily on Voyager observations and ground-based stellar occultation data summarized in Yelle et al. [14] Due to the relative scarcity of observational data for Titan during Titan-GRAM development, a simplified approach to atmospheric variability and uncertainty was adopted through the use of a prescribed envelope of minimum-average-maximum density versus altitude. Fig. 1 shows this envelope for Titan. In Titan-GRAM, atmospheric variability and measurement uncertainty are superimposed on a given mean profile through the selection of appropriate values for input parameters Fminmax and rpscale. Fminmax values are allowed to vary within the range $-1 \leq \text{Fminmax} \leq 1$ according to Table 1. The rpscale parameter, a random perturbation scale factor, may assume values within the range $0 \leq \text{rpscale} \leq 2$. Fig. 2 is a sample plot showing how Fminmax and rpscale are utilized to generate perturbed density profiles for Monte Carlo trajectory analysis.

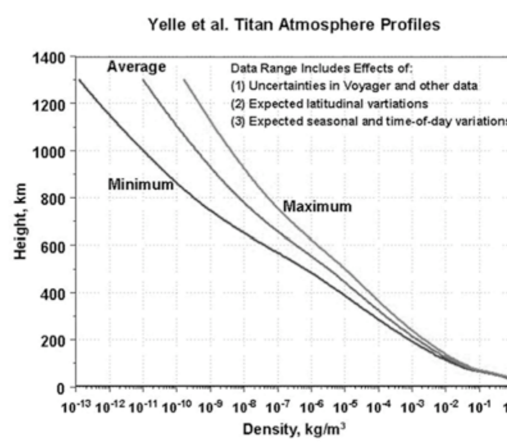

Fig. 1. Yelle Minimum, Average, and Maximum density profiles form the original basis for Titan-GRAM

Titan-GRAM includes an option for using Titan General Circulation Model (GCM) data as input. The Titan GCM data derives from the model of Hourdin et al. [15] Temperature and zonal wind versus pressure level at Ls = 0º and Ls = 180º are used as reference values, while estimates for other seasons are extrapolated using 180-degree Ls offset and hemispheric reversal. Upper altitudes in the GCM option are characterized by a parameterized fit to Titan exospheric temperatures from Mueller-Wodarg [16]. Output generated with the Titan-GRAM GCM option compares favorably with Infrared Space Observatory (ISO) data analyzed by Coustenis et al. [17], as shown in Fig. 3. However, both GCM and ISO profiles show a general bias of up to +25% deviation from the Yelle average profile.

Table 1. Fminmax Values Characterize Seasonal and Time-of-Day Variability

Effect	Fminmax negative	Fminmax near zero	Fminmax positive
Latitudinal/ Seasonal	Winter/polar latitudes	Near-equatorial latitudes Equinox, all latitudes	Summer/ polar latitudes
Time of Day	Night	Near twilight	Day

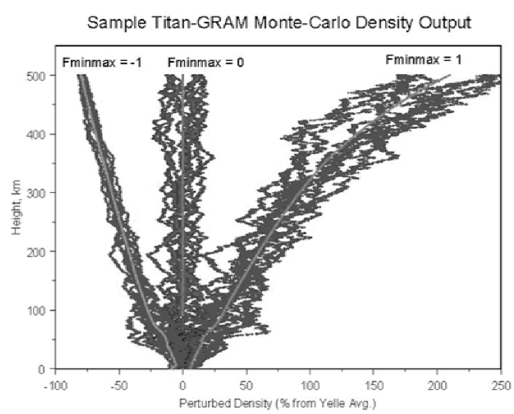

Fig. 2. Titan-GRAM perturbed densities (% deviation from Yelle Average density)

3. TITAN-GRAM COMPARISONS WITH CASSINI ORBITER OBSERVATIONS

Titan-GRAM 2004 was exercised by members of an independent technical assessment and inspection (ITA/I) team during Titan atmospheric entry analysis for the international Cassini-Huygens mission. Cassini-Huygens, a joint endeavor by the ESA, NASA, and the Italian Space Agency, is currently conducting a detailed four-year study of the Saturnian system, including Saturn's moon Titan. The Cassini-Huygens spacecraft, an orbiter-probe system, was successfully launched from Cape Canaveral on October 15, 1997. The Cassini orbiter entered the Saturnian system in July, 2004 and successfully released the Huygens scientific probe toward Titan on December 25, 2004. The Huygens probe, scheduled to enter Titan's atmosphere at 10:14 UTC, January 14, 2005, will collect atmospheric and surface data during its entry, descent, and landing (EDL) mission phase.

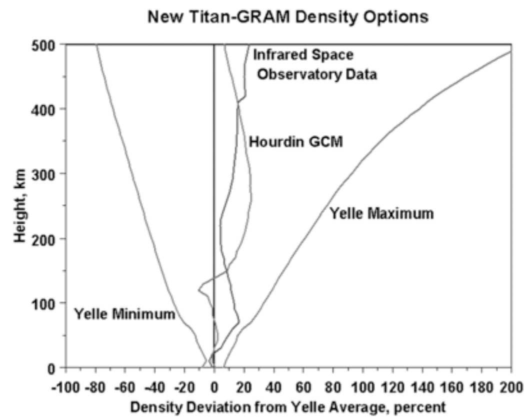

Fig. 3. Yelle Minimum, Yelle Maximum, and GCM Density Deviations from Yelle Average compared with Infrared Space Observatory Measured Density Deviation from Yelle Average

The Huygens EDL ITA/I, sponsored by the NESC at the request of ESA, included high-fidelity flight simulation, parachute modeling, atmospheric modeling, aerodynamic database development, and aerothermodynamic environment modeling. Titan-GRAM was utilized in Monte Carlo trajectory simulations for the Huygens probe. In the atmospheric modeling portion of the project, a new Titan-GRAM option was developed to read in auxiliary input profiles of thermodynamic and/or wind data within a user-specified region. The new option allowed Titan-GRAM to ingest Cassini flyby data provided by the Titan Atmospheric Model Working Group (TAMWG), thus enabling comparisons between TAMWG flyby profiles and the Yelle profiles that form the original basis for Titan-GRAM.

In preparation for Cassini's first targeted flyby of Titan (Titan-A) on October 26, 2004, the TAMWG met for purposes of constructing a representative baseline (T0) Titan atmosphere profile. The T0 profile incorporated data acquired by Cassini during its July 2, 2004 T0 flyby: Composite Infrared Spectrometer (CIRS) temperature retrievals; Visual and Infrared Mapping Spectrometer (VIMS) temperatures and CO/CO_2 abundances; wind speeds from cloud measurements by Cassini's Imaging Science Subsystem (ISS) and from ground-based measurements; and atmospheric densities derived from stellar occultation observations by Cassini's Ultraviolet Imaging Spectrograph Subsystem

(UVIS). Fig. 4 expresses the preliminary TAMWG T0 density profile in terms of density percent deviation from the Yelle average density profile, compared with the Yelle minimum and maximum density deviations from average. In general, the T0 density profile exhibits a positive bias with respect to the Yelle average profile, increasing to a maximum of +120% percent deviation from the Yelle average at altitudes near 800 km.

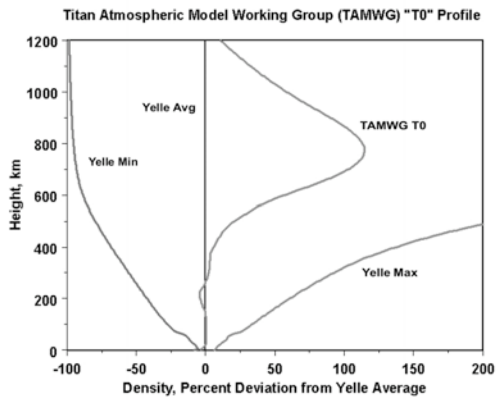

Fig. 4. Preliminary TAMWG T0 density deviation from Yelle Average compared with Yelle Minimum and Maximum density deviations from Yelle Average

The TAMWG eventually developed a range of T0 profiles to address the uncertainties inherent in estimates of major constituent concentrations, most notably methane. Atmospheric methane is a "greenhouse" gas and uncertainties in methane mole fraction give rise to temperature uncertainties. Methane is also of interest in outer planetary aeroentry studies because it adds a strong radiative heating component to the total heat flux and total heat load on an aeroentry vehicle. Table 2 lists the range of major constituent mole fractions represented by the T0 series of profiles. Fig. 5 expresses the associated T0 density profiles in terms similar to Fig. 4. As a consequence, estimates of temperature uncertainty were applied as bounds to the nominal T0 temperature (Fig. 6) and density (Fig. 7) profiles.

In mid-November 2004, observational data from Cassini's Titan-A flyby became available for model comparisons. The Titan-A flyby provided the very first in-situ sampling of Titan's atmosphere. Fig. 8 compares TAMWG Titan-A temperature profiles with their T0 predecessors. Fig. 9 compares the corresponding Titan-A and T0 density profiles. While the Titan-A profiles utilize a more conservative value for methane mole fraction than their T0 counterparts, they exhibit less temperature uncertainty due to a higher reliance on CIRS temperature retrievals.

Table 2. TAMWG T0 Profile Series Major Constituent Mole Fractions

Profile	N_2% / CH_4% / Ar%	Description
T0_0	98.1(-) / 1.9(+) / 0	Nominal CH_4 Low Ar
T0_1	91.1(-) / 1.9(+) / 7	Nominal CH_4 High Ar
T0_2	99.0(-) / 1.0(+) / 0	Low CH_4 Low Ar
T0_3	92.0(-) / 1.0(+) / 7	Low CH_4 High Ar
T0_4	97.0(-) / 3.0(+) / 0	High CH_4 Low Ar
T0_5	90.0(-) / 3.0(+) / 7	High CH_4 High Ar

(-): lower values in troposphere
(+): higher values in troposphere

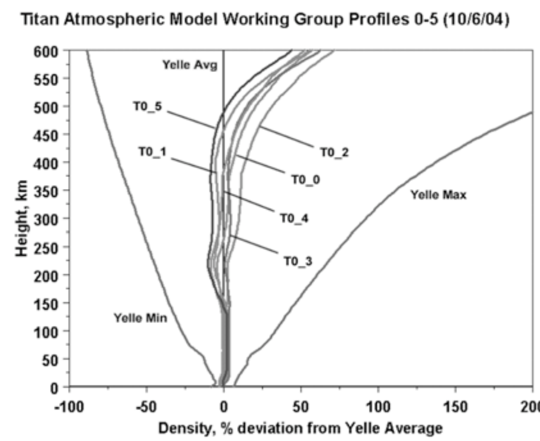

Fig. 5. TAMWG T0 Series density deviations from Yelle Average compared with Yelle Minimum and Maximum density deviations from Yelle Average

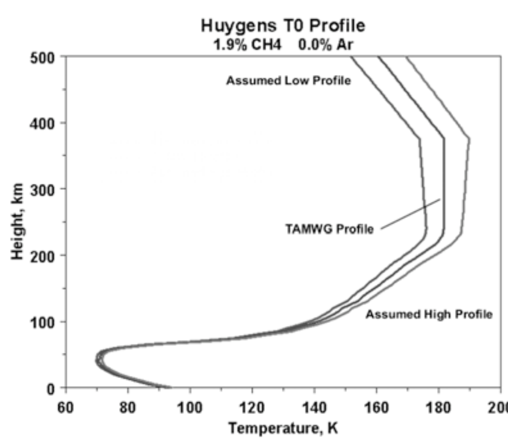

Fig. 6. TAMWG T0 Low, Nominal, and High temperature profiles incorporating uncertainty

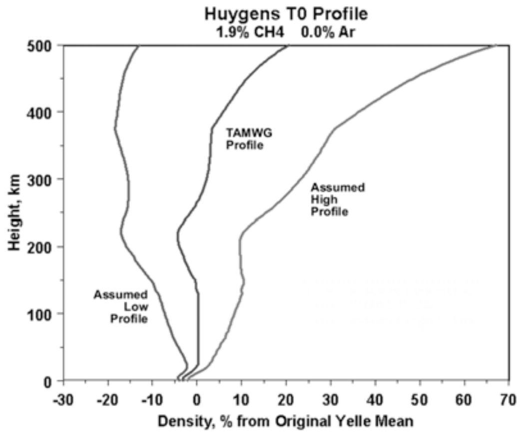

Fig. 7. TAMWG T0 Low, Nominal, and High density profiles incorporating temperature uncertainty

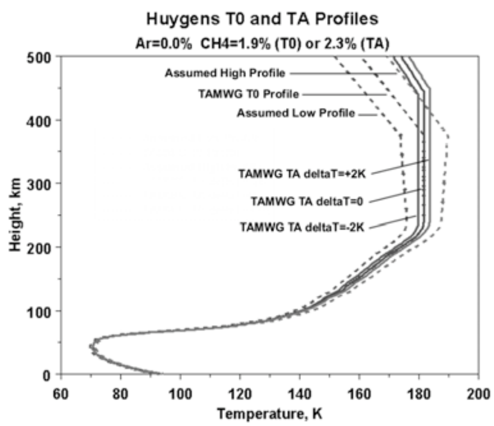

Fig. 8. Comparison of TAMWG Titan-A and T0 Low, Nominal, and High Temperature Profiles

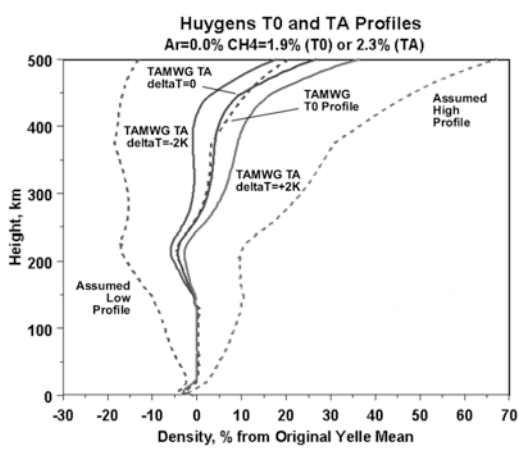

Fig. 9. Comparison of TAMWG Titan-A and T0 Low, Nominal, and High Density Profiles

Cassini's ISS measured prograde (eastward) wind velocities of 34 m/s ± 10 m/s at about 40 km altitude and 10 m/s at Titan's surface. Based on wind observations, the TAMWG established a recommended value for mean wind velocity of 130 m/s with standard deviation 30 m/s for altitudes ≥ 200 km. Because the observed velocities corresponded closely with Titan-GRAM predicted values (Fig. 10), Titan-GRAM was recommended by the TAMWG as the official Huygens probe entry wind model.

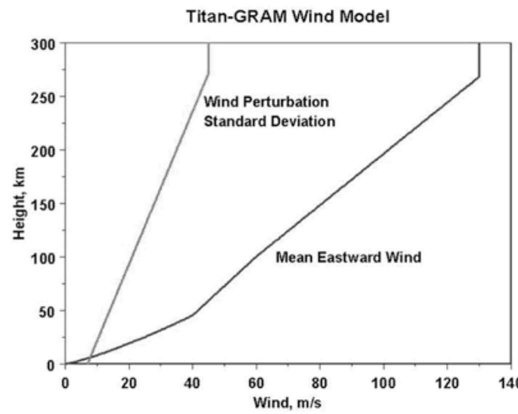

Fig. 10. Titan-GRAM Huygens Entry Wind Model

Measurement uncertainty will continue to play a role in atmospheric density characterizations. Titan-A mass densities inferred from Cassini's Attitude and Articulation Control System (AACS) and measured INMS mass densities vary by a factor of almost four. Investigation into measurement discrepancies, and analysis of upcoming Huygens EDL and Cassini flyby data, will undoubtedly drive refinements to the Yelle model upon which Titan-GRAM is based.

4. MARS-GRAM 2005 VALIDATION AND APPLICATION

Mars-GRAM 2005, formally released in March, 2005, represents the latest version of Mars-GRAM. Two new features of Mars-GRAM 2005 that are of interest for aeroassist applications are:

1) Option to use input data sets from MGCM and MTGCM model runs that were designed to closely simulate the conditions observed during the first two years of TES observations at Mars (TES Year 1 = April 1999 through January 2001; TES Year 2 = February 2001 through December 2002).

2) Option to read and use any "auxiliary profile" of temperature and density versus altitude.

Comparisons of Mars-GRAM 2005 General Circulation Model climatology with Mars Global

Surveyor Thermal Emission Spectrometer (TES) limb data [18] are enabled through the Mars-GRAM auxiliary profile option. Fig. 11 compares atmospheric density profiles from Mars-GRAM 2005 and TES limb data at representative Mars Phoenix landing conditions (Ls = 78 degrees, latitude = 67.5N, longitude = 223.1E, for limb data from TES Year 1). The TES limb data profile in Fig. 11 is an average of 17 individual limb profiles that are near this location and time. Fig. 11 shows good agreement between Mars-GRAM 2005 and TES limb densities for heights up to about 30 km, and above about 50 km. Mars-GRAM 2005 density becomes about 15% higher than TES limb density near 40 km altitude.

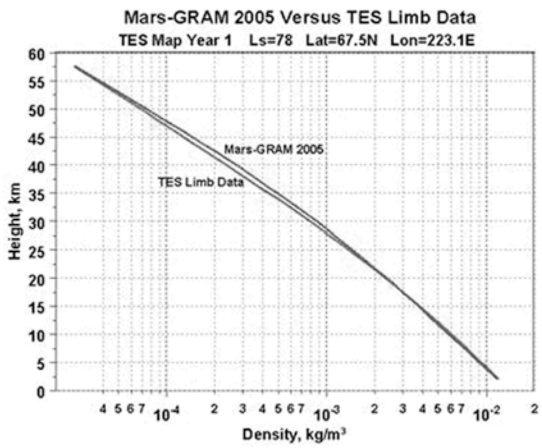

Fig. 11. Density profiles from Mars-GRAM 2005 and TES limb data at representative Mars Phoenix landing conditions

Fig. 12 compares Mars-GRAM 2005 density at equatorial conditions for Ls=120 with both TES limb data and TES nadir data. TES limb and nadir data agree quite well with each other, over the full height range for which nadir data are available. Figure 3 shows that Mars-GRAM 2005 density agrees well with both types of TES data, up to a height of about 30 km. However, Mars-GRAM 2005 densities begin to deviate (on the low side) from TES limb data above about 30 km, with Mars-GRAM densities being about 40% lower than TES limb data between about 45 km and 55 km.

Preliminary studies by Murphy[1] using various vertical dust profiles suggest that the tendency of Mars-GRAM climatology to yield a cold bias results from too little dust at upper altitudes in the nominal Mars General Circulation Model (MGCM) vertical dust distribution.

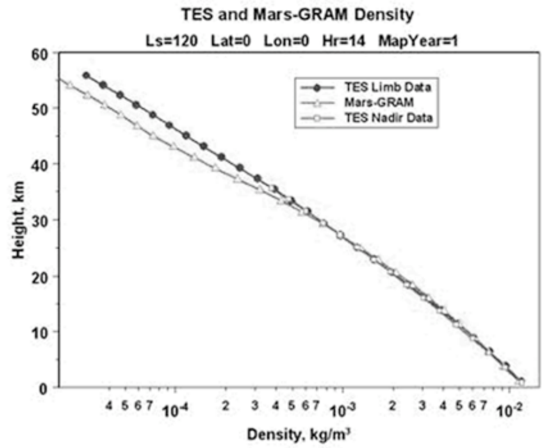

Fig. 12. Density profiles from Mars-GRAM 2005, TES nadir data, and TES limb data at 0º latitude for Ls = 120º

Detailed comparisons between Mars-GRAM global dust optical depth distributions (Figs. 13 and 14) and representative TES Year 1 and 2 observations are currently in progress as part of an ongoing ISP-sponsored Mars-GRAM aerocapture systems analysis follow-on to [19].

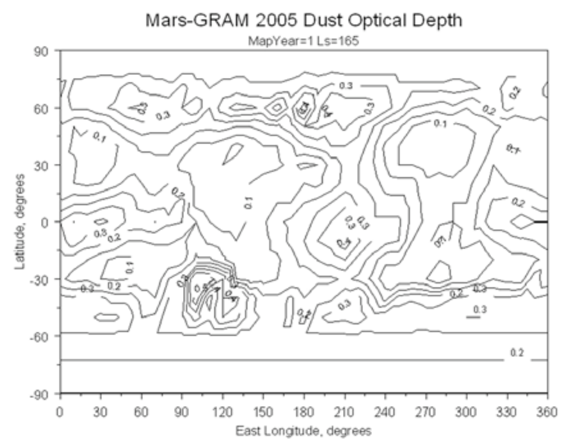

Fig. 13. Mars-GRAM 2005 latitude-longitude cross section of dust optical depth, MapYear = 1, Ls = 165º

5. CONCLUSIONS

Titan-GRAM was originally developed for the purpose of incorporating atmospheric variability and uncertainty in Monte Carlo trajectory simulations associated with Titan aerocapture systems analysis studies. Since its inception, Titan-GRAM has also found use in Cassini-Huygens EDL simulations and in comparative analysis of observational data. Titan-GRAM's flexibility is representative of all the models in the GRAM

[1] Private communication, 13 Jan. 2005.

series. GRAM, Mars-GRAM, Neptune-GRAM,

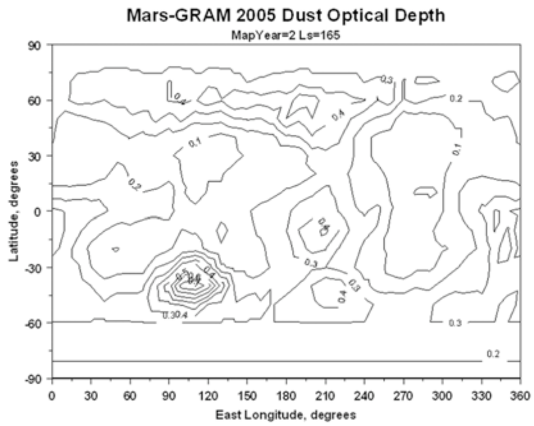

Fig. 14. Mars-GRAM 2005 latitude-longitude cross section of dust optical depth, MapYear = 2, Ls = 165º

and Venus-GRAM share Titan-GRAM's capability to model atmospheric variability and uncertainty for a wide variety of aeroassist applications. Within the context of NASA's Vision for Space Exploration, GRAM and Mars-GRAM have the highest potential for utilization in EDL studies. However, continued technology investment in aeroassist applications warrants sustainment of all models in the GRAM series.

6. ACKNOWLEDGMENTS

The authors gratefully acknowledge support from MSFC's ISP program and the NASA Engineering Safety Center (NESC). Particular thanks go to Bonnie James (MSFC), Manager of Aerocapture Technology, Michelle Munk (MSFC), Lead Systems Engineer for Aerocapture Technology, and Melody Herrmann (MSFC), Manager of Technology Planning and Systems Analysis. Steven Labbe (JSC), Richard W. Powell (LaRC), and Mary Kae Lockwood (LaRC) are acknowledged for their leadership and direction of the Huygens EDL ITA/I Team. Special thanks are extended to Roger Yelle of the TAMWG for assistance in obtaining Cassini T0 and Titan-A data.

7. REFERENCES

1. Lockwood, M. K., "Neptune Aerocapture Systems Analysis", Paper AIAA 2004-4951, presented at the AIAA Atmospheric Flight Mechanics Conference and Exhibit, August 16-19, 2004, Providence, Rhode Island.

2. Lockwood, M. K., "Titan Aerocapture Systems Analysis", Paper AIAA 2003-4799, presented at the 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 20-23, 2003, Huntsville, Alabama.

3. Justus, C. G., Woodrum, A., Roper, R. G., and Smith, O. E., "A Global Scale Engineering Atmospheric Model for Surface to Orbital Altitudes, I: Technical Description", NASA TMX-64871, Marshall Space Flight Center, Alabama, 1974.

4. Justus, C. G., Fletcher, G. R., Gramling, F. E., and Pace, W. B., "The NASA Global Reference Atmospheric Model - MOD 3 (With Spherical Harmonic Wind Model)", NASA CR-3256, Contract NAS8-32897, 1980.

5. Justus, C. G., Alyea, F. N., Cunnold, D. M., Blocker, R. A., and Johnson, D. L., "GRAM-88 Improvements in the Perturbation Simulations of the Global Reference Atmospheric Model", NASA Special Report ES44-11-9-88, 1988.

6. Justus, C. G., Alyea, F. N., Cunnold, D. M., Jeffries III, W. R., and Johnson, D. L., "The NASA/MSFC Global Reference Atmosphere Model - 1990 Version (GRAM-90), Part I: Technical/Users Manual", NASA TM-4268, Grant NAG8-078, 1991.

7. Justus, C. G., Jeffries III, W. R., Yung, S. P., and Johnson, D. L., "The NASA/MSFC Global Reference Atmospheric Model - 1995 Version (GRAM-95)", NASA TM-4715, 1995.

8. Justus, C. G., and Johnson, D. L., "The NASA/MSFC Global Reference Atmospheric Model - 1999 Version (GRAM-99)", NASA/TM-1999-209630, Marshall Space Flight Center, Alabama, 1999.

9. Justus, C. G., "Mars Global Reference Atmospheric Model for Mission Planning and Analysis", *Journal of Spacecraft and Rockets*, Vol. 28, No. 2, 216-231, 1991.

10. Justus, C.G., and Johnson, D.L., "Mars Global Reference Atmospheric Model 2001 Version (Mars-GRAM 2001) Users Guide", NASA/TM-2001-210961, April, 2001.

11. Justus, C. G., James, B. F., Bougher, S. W., Bridger, A. F. C., Haberle, R. M., Murphy, J. R., and Engel, S., "Mars-GRAM 2000: A Mars Atmospheric Model for Engineering Applications",

Advances in Space Research, Vol. 29, 193-202, 2002.

12. Justus, C. G., Duvall, A. L., and Johnson, D. L., "Earth Global Reference Atmospheric Model (GRAM-99) and Trace Constituents", *Advances in Space Research*, Vol. 34, 1731-1735, 2004.

13. Justus, C. G., Duvall, A. L., and Johnson, D. L., "Mars-GRAM Validation with Mars Global Surveyor Data", *Advances in Space Research*, Vol. 34, 1673-1676, 2004.

14. Yelle, R. V., Strobel, D. F., Lellouch, E., and Gautier, D., "Engineering Models for Titan's Atmosphere", in *Huygens: Science, Payload, and Mission*, ESA SP-1177, August, 1997.

15. Hourdin, F., Talagrand, O., Sadourny, R., Courtin, R., Gautier, D., and McKay, C. P., "Numerical Simulation of the General Circulation of the Atmosphere of Titan", *Icarus*, Vol. 117, 358-374, 1995.

16. Mueller-Wodarg, I. C. F., "The Application of General Circulation Models to the Atmospheres of Terrestrial-Type Moons of the Giant Planets", manuscript in AGU monograph *Comparative Atmospheres in the Solar System*, Ed. M. Mendillo, A. Nagy, H. Waite, American Geophysical Union, 2002.

17. Coustenis, A., Salama, A., Schulz, B., Ott, S., Lellouch, E., Encrenaz, T. H., Gautier, D., and Feuchtgruber, H., "Titan's Atmosphere from ISO Mid-Infrared Spectroscopy", *Icarus*, Vol. 161, Issue 2, 383-403, 2003.

18. Conrath, B. J., Pearl, J. C., Smith, M. D., and Christensen, P. R., "Mars Global Surveyor TES Results: Atmospheric Thermal Structure Retrieved from Limb Measurements," 49.08, American Astronomical Society, 31st Annual Meeting of the Division of Planetary Sciences, Padua, Italy, October 10-15, 1999.

19. Oberto, Bob, et al., "Advanced Projects Design Team Mars Aerocapture Option 2", Jet Propulsion Laboratory Report ID #X-746, August 19, 2004.